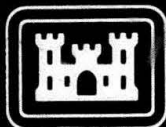Cold Regions Technical Digest
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Electrical Grounding in Cold Regions

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Electrical grounding in cold regions

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Introduction

Electrical grounding for temporary and permanent installations in cold regions is complicated by the existence of frozen soil. This is because

- The electrical resistivity of frozen soil can be several orders of magnitude higher than unfrozen soil.
- The contact resistance between the grounding electrodes and the soil, which is usually negligible under unfrozen conditions, can become significant if a veneer of ice forms on the electrode.
- It is difficult to drive grounding rods into frozen soil.

The purpose of this digest is to describe the factors to consider when planning a grounding system for permanent and temporary installations in regions of seasonal frost and permafrost.

**Electrical conductivity of earth material**

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Electrical conduction is the flow of an electrical charge in response to a difference in electric potential. Electrical resistivity ϱ is a measure of the difficulty of current flow through a substance and is commonly expressed in ohm-centimeters (Ω-cm). It is related to the measured resistance R of an electrical system by

$$\varrho = \frac{RA}{L} \tag{1}$$

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1. Variation in resistivity of soils as a function of water content. (After Tagg 1964.)
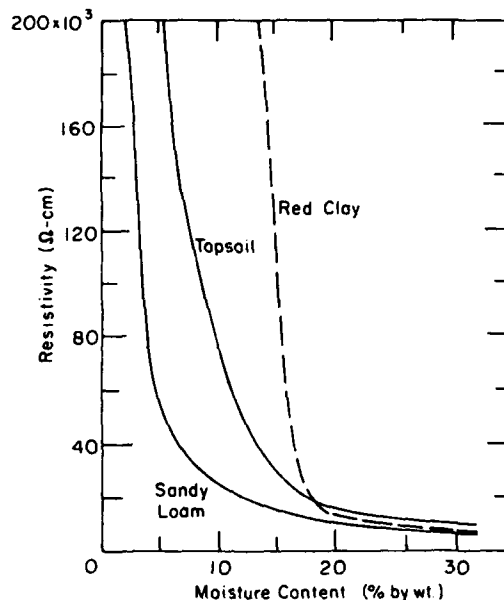
where A is the cross-sectional area of the conductor (cm²), and L is the length of the conductor (cm). Conductivity is the reciprocal of resistivity and is usually expressed in mhos per meter.

Low-frequency and DC current may flow through earth materials by the movement of either ions or electrons. Conduction by electrons is usually restricted to metals since most other materials do not contain enough free electrons to carry electricity. Electrical current in earth materials is usually carried by ions that are contained in water that is either in the spaces between particles or attached to particle surfaces. The conductivity of most earth materials, then, is primarily a function of the concentration and mobility of ions. Consequently the amount of water in a soil strongly influences conductivity, but only up to a water content of about 18% (Fig. 1) (Tagg 1964). Electrical conductivity generally increases with decreasing grain size because finer-grained soil has more surface area per unit volume and therefore holds more adsorbed water than coarse-grained soil. Very fine soils may also contain clay minerals holding diffuse layers of ions that are free to migrate under the influence of an electric field, providing an additional electrical path.

The resistivity of frozen soil is generally controlled by temperature, ice volume and soil type (the influence of soil type is probably largely due to grain size effects). Figure 2 shows the
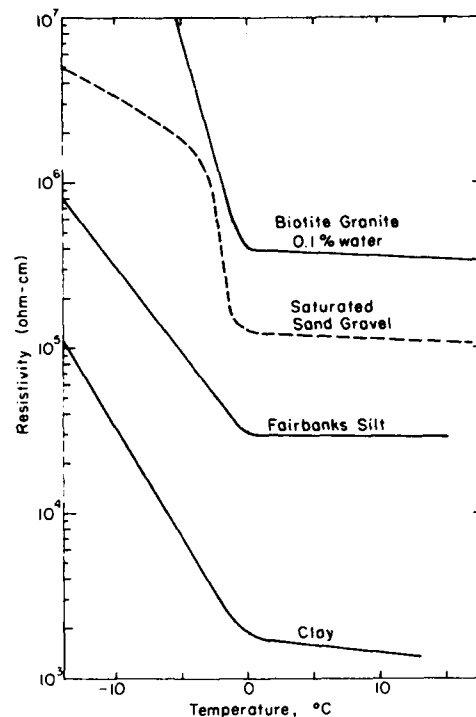
2. *Resistivities of some soils and one rock type as a function of temperature. (After Hoekstra and McNeill 1973.)*

influence of temperature and soil type on resistivity. The relatively low resistivities at or slightly below the freezing point are due to unfrozen water films adsorbed on soil particles. The water in these films has a depressed freezing point, and because these films are usually connected, they provide a conductive path (Society of Exploration Geophysicists 1967). The conductivity is enhanced by the increasing concentration of dissolved salts in the unfrozen water as water freezes and rejects salts and other impurities. Figure 3 is a graph of unfrozen water content as a function of temperature for five soils.

Large seasonal variations in resistivity in areas of seasonal frost and permafrost reflect variations in temperature and water content. This is illustrated in Figure 4, which was developed by substituting resistivity values from laboratory measurements on saturated organic silt for seasonal temperature data. Figure 5 is a summary of field resistivity data for both frozen and unfrozen materials as measured by three geophysical techniques.

3. Unfrozen water content as a function of temperature for fine soils. (From Anderson and Morgenstern 1973.)
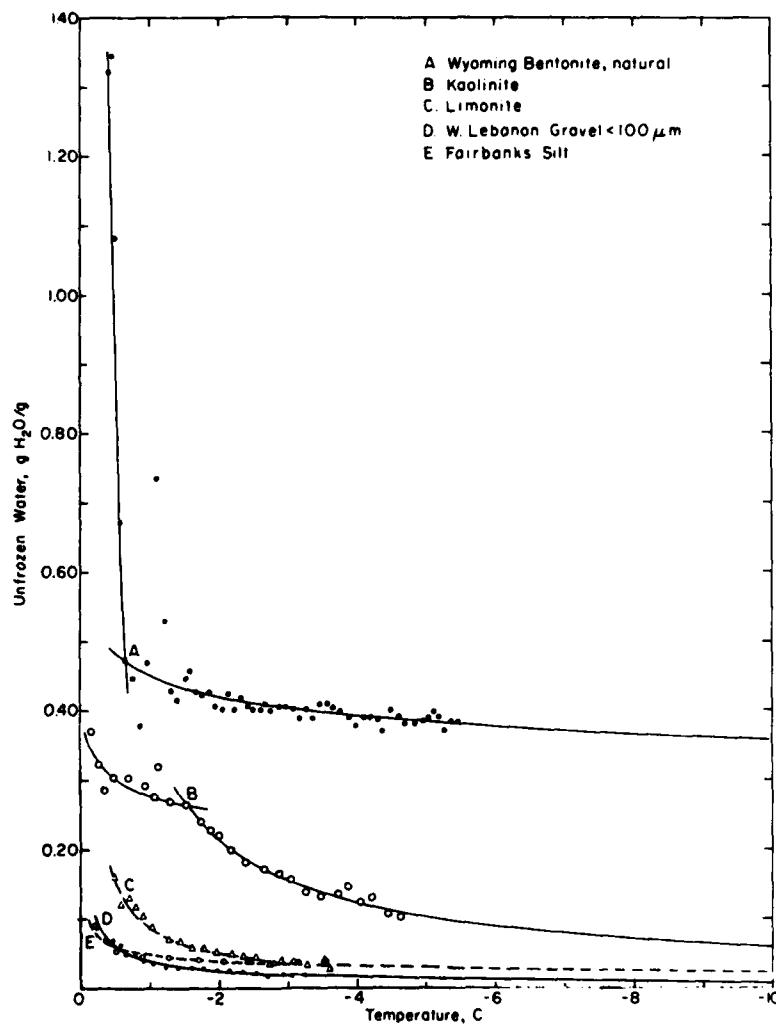
4. Annual temperature data for Fairbanks, Alaska, translated into equivalent resistivity values in ohm-cm based on laboratory measurements for saturated organic silt. (From Arcone et al. 1979.)

FROZEN
- SILT / FAIRBANKS AK GLENNCK
- SILT / FAIRBANKS AK-GOLDSTREAM
- SILTY CLAY / GULKANA AK

THAWED
- GRANITE / CANAAN NH
- SAND / HANOVER NH
- SILTY SAND / TORONTO ONTARIO
- SANDY SILT IT... / PLAINFIELD NH
- SANDY SILT IT... / TORONTO ONTARIO
- SILT / FAIRBANKS AK-GLENNCK
- SILT / FAIRBANKS AK FIELD STATION
- SILT / FAIRBANKS AK-GOLDSTREAM
- SILTY CLAY / GULKANA AF
- CLAY / LEBANON NH

LOW FREQUENCY RADIOHM
MAGNETIC INDUCTION
WENNER PROBE

10^3 10^4 10^5 10^6

Apparent Resistivity (ohm–cm)

5. *Apparent resistivity of various materials measured with three techniques. (From Sellmann et al. 1976.)*
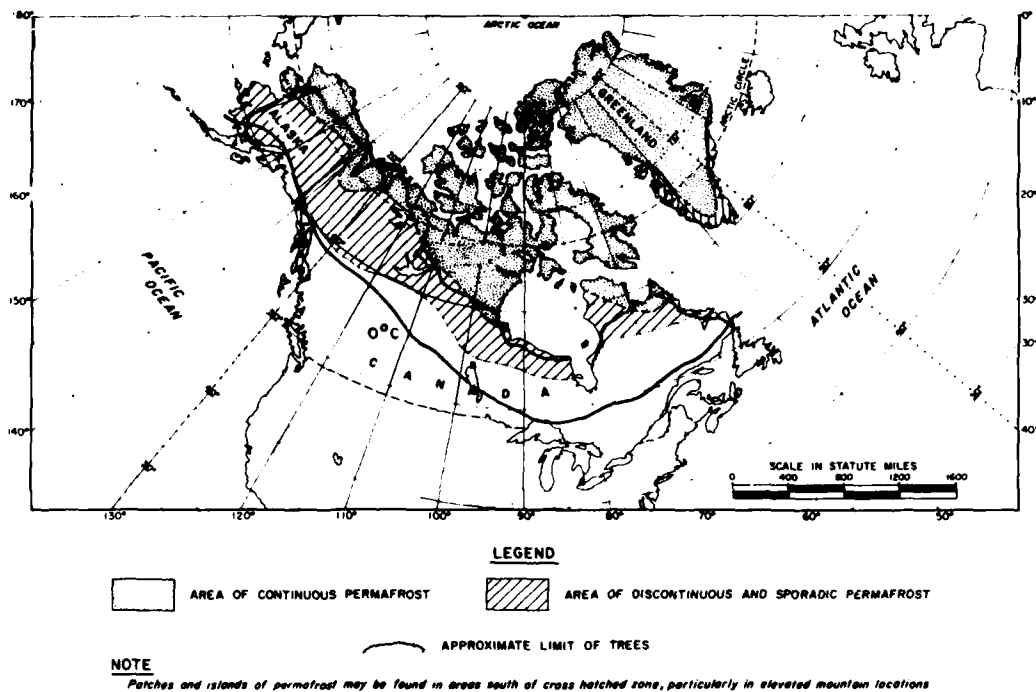
Evaluating a site

The performance of a grounding installation depends primarily on the resistivity of the soils at the grounding site. Large local and regional variations in the resistivities of soils, particularly in areas of frozen ground, make careful site study and selection a worthwhile means of assuring the best possible ground.
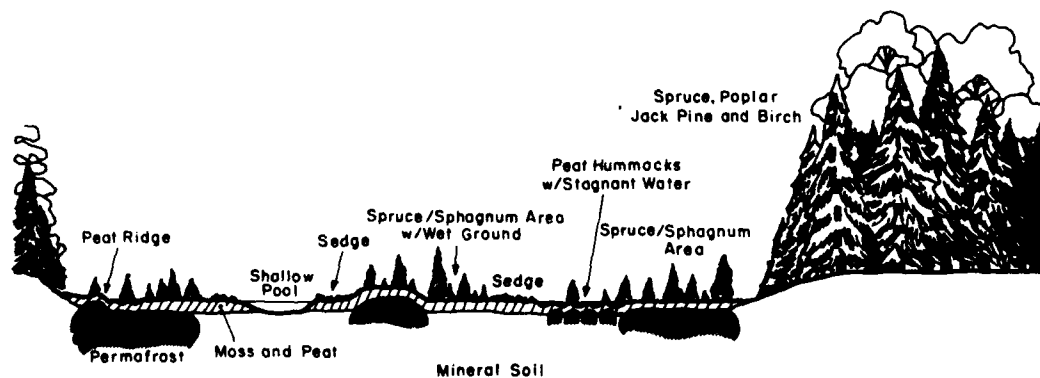
Permafrost

Areas where the ground is seasonally frozen but the deeper subsurface soils remain permanently unfrozen are known as areas of seasonal frost. Permafrost, or perennially frozen ground, refers to areas where the ground temperatures remain below 0°C (32°F) for at least two years (Muller 1947). Some sections of permafrost contain such large quantities of ice that it is impossible to obtain an acceptable ground.

Permafrost regions can be subdivided into zones of continuous and discontinuous permafrost. In the Northern Hemisphere the southern limit of discontinuous permafrost is roughly delineated by the 0°C mean annual isotherm (Fig. 6). The southern limit of continuous permafrost begins where the mean annual air temperature is several degrees lower (in

LEGEND

☐ AREA OF CONTINUOUS PERMAFROST　　　　▨ AREA OF DISCONTINUOUS AND SPORADIC PERMAFROST

⌐⌐ APPROXIMATE LIMIT OF TREES

NOTE
Patches and islands of permafrost may be found in areas south of cross hatched zone, particularly in elevated mountain locations

6. Permafrost zones in North America.

7. Profile through peatland in a discontinuous permafrost zone showing the relation of permafrost to topography and vegetation. (From Brown 1977.)

Canada it corresponds to about the –8°C isotherm) (Washburn 1980).

The existence of permafrost also varies with altitude and local conditions. Figure 7 shows how topography can affect the vertical and horizontal distribution of permafrost in a discontinuous permafrost zone. Some recurring surface features in permafrost regions can be helpful in finding unfrozen, low-

resistivity sites. Some examples, taken from several sources (Muller 1947, Kane and Slaughter 1973, Sherman 1973, Williams and Everdingen 1973), are

- Trees with tap roots, such as pines, indicate that permafrost is either absent or deep.
- Willow groves generally indicate the presence of groundwater that freezes for only a short period.
- Tamarack, spruce and dwarfed and stunted birches may indicate a shallow permafrost table.
- Peat and moss usually indicate a relatively thin water-bearing zone above permafrost.
- Lakes and rivers usually depress the permafrost table locally and therefore may overlie unfrozen aquifers. Other local topographic depressions may indicate areas of thaw.
- In the zone of discontinuous permafrost, it is likely that the thawed material beneath many lakes may have a hydrologic (and thus electrical) connection with subpermafrost aquifers.
- In coastal areas, saline groundwater may be found at shallow depths beneath bars, spits, beaches or deltas.

Surface and subsurface investigations for construction purposes usually include soils analyses and determination of the depth and thickness of the permafrost or the annually frozen zone or both. These data, as well as information about surface and groundwater supplies, are helpful in selecting grounding sites.

Geophysical measurements

Electrical geophysical methods that directly measure earth resistivity are useful in evaluating grounding sites. Two methods most likely to be useful are the DC resistivity method and the electromagnetic method. For a review of all geophysical methods used in studying permafrost distribution, see Scott et al. (1978).

The DC resistivity method uses a current passed between two end electrodes in a four-electrode array placed in a straight line in the ground; the resulting potential difference is measured between the central two electrodes and indicates an average resistivity. The depth to which an integrated average of resistivity can be measured increases with increased spacing of the electrodes; however, lateral resolution is lost with increasing depth of penetration. Telford et al. (1976)

and the Society of Exploration Geophysicists (1967) described common methods more completely.

Inductive electromagnetic methods use alternating current sources to produce an electromagnetic field that induces eddy currents in the ground. An induced field produced by the eddy currents is detected at a receiver. The difference in magnitude between the induced fields and the inducing fields results from the conductivity of the earth. The depth of penetration is controlled primarily by the spacing of the transmitter and the receiver. Small, portable units are commercially available for studying near-surface lateral distribution of electrical resistivity, and these have been used for mapping the distribution of shallow permafrost (Hoekstra et al. 1975, Arcone et al. 1979). These methods can be used year-round, whereas DC methods are difficult to use in the winter because of high contact resistance at the electrodes.

Choosing
a grounding
method

Some grounding systems that have been used in cold regions are

- Vertical rods driven into the earth,
- Arrays of many vertical rods,
- Horizontal strip electrodes buried in the earth,
- Direct electrical connection to the ocean,
- Electrical connection to continuous metal well casings (water or petroleum),
- Electrical connection to steel in reinforced concrete foundations of buildings, and
- Electrodes placed in the unfrozen beds of lakes and streams.

The first three methods are the most common.

Vertical
rods

The most common method of achieving an electrical ground is by driving one or more steel rods into the earth. In the simplest case of a homogeneous earth and negligible contact resistance, the resistance to ground of a single electrode is estimated using the following equation (Tagg 1964):

$$R_g = \frac{\varrho}{2\pi\ell}\left[\ln\frac{4\ell}{\alpha} - 1\right] \tag{2}$$

where R_g = resistance to ground (ohms)
       ϱ = resistivity of the soil (ohm-cm)
       ℓ = length of the rod (cm)
       α = radius of the rod (cm).

Equation 2 indicates that if both the rod length and radius are increased by the same proportions, the length increase will have a larger influence on lowering R_g than the increase in diameter, as demonstrated in Figure 8. Doubling the length of the rod will lower the resistance to ground by about 40%; much larger increases in the diameter are needed to produce the same results. In many cases it will be most practical to use a longer electrode, especially in seasonal frost areas where more conductive soils are likely to occur at depth.
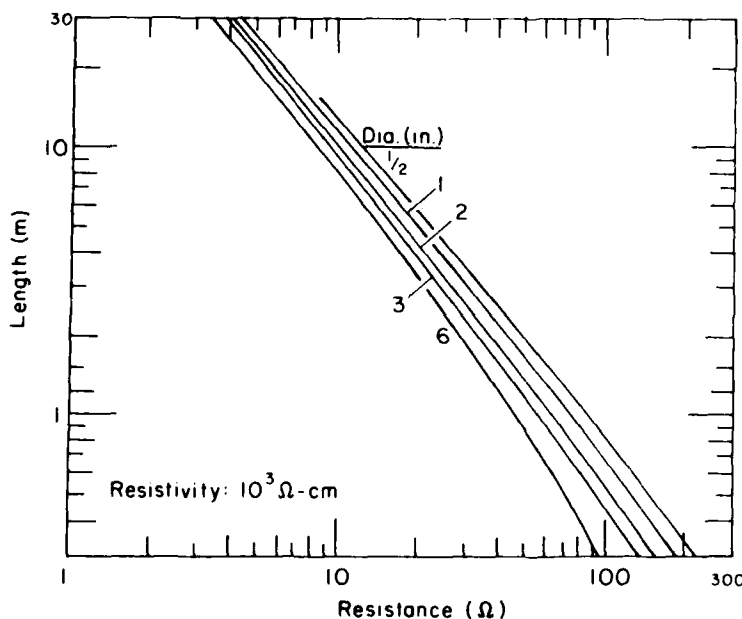
Connecting grounding electrodes in parallel will produce a lower R_g than can be obtained with a single rod. Because each rod is affected by the field of the others, the rod spacing must be at least equal to the depth of the rods. The combined resistance of two vertical rods connected in parallel can be calculated by the following equation (Tagg 1964):
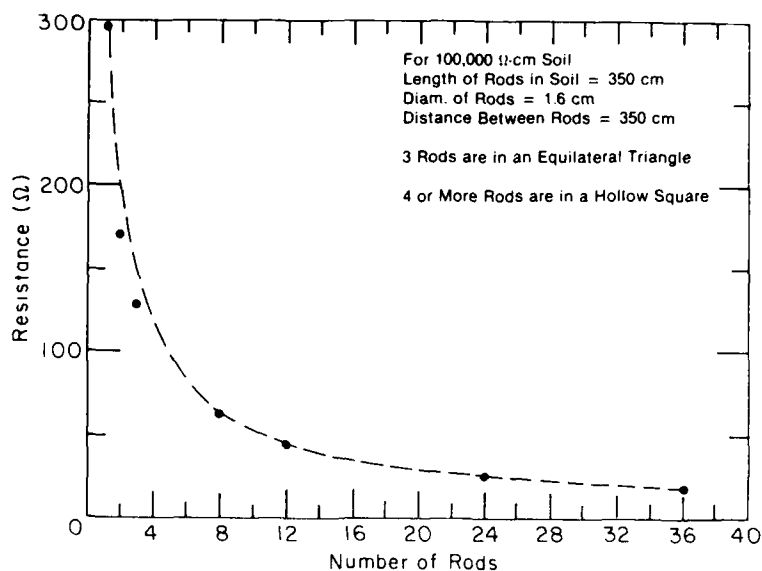
Multiple-rod arrays

$$R_g = \frac{\varrho}{4\pi r} \left[1 + \frac{r}{d} \right] \tag{3}$$

where d is the distance between the rods and r is the radius of a hemisphere in the earth having the same resistance as the driven rod. The radius r is calculated from

$$r = \frac{\ell}{\ln(4\ell/\alpha)-1} . \tag{4}$$

8. Resistance of a driven rod in 10,000 Ω-cm soil. (From Tagg 1964.)

9. Resistance vs number of electrodes in 100,000 Ω-cm soil.

Connecting two grounding rods in parallel can decrease R_g by a factor of about two compared to a single rod. As the number of rods increases, the effect of each rod decreases (Fig. 9). For example, one hundred 1.3-cm (½-in.) diameter grounding rods arranged in a hollow square driven to a depth of 1.2 m (4 ft) with 1.2 m between each rod would decrease R_g by a factor of 30 compared to a single rod. Tagg (1964) described methods for calculating the resistances of large numbers of electrodes connected in parallel in various configurations.

Horizontal strip electrodes

Buried, horizontal wire or strip electrodes may be used when bedrock or permafrost is less than 2 m from the surface.* In permafrost regions it would be most practical to install the electrode during the summer when the active layer is thawed.

Table 1 lists equations for calculating the resistance of various configurations of buried wire. Table 2 gives examples of the results of these calculations. The resistance of buried strips can be approximated by performing the calculations for a wire of the same circumference.

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* Buried plate or ring electrodes have also been used to achieve grounding but have been found to be less practical than driven rods or buried wire or strip electrodes. See Tagg (1964) for a discussion and resistance calculations for these grounding methods.

Table 1. Earth resistances for buried wires of radius α at depth $S/2$ (Tagg 1964).
(Units should be consistent throughout the calculations.)

Configuration	Resistance formula
Single wire (wire length = $2L$)	$R_g = (\varrho/4\pi L)\{\ln(4L/\alpha)-1 + \ln[(2L + \sqrt{S^2 + 4L^2})/S] + S/2L - \sqrt{S^2 + 4L^2}/2L\}$
Right-angle turn (L = length of one arm)	$R_g = (\varrho/4\pi L)\{\ln(2L/\alpha) + \ln(2L/S) - 0.2372 + 0.2146(S/L) + 0.1035(S^2/L^2) - 0.0424(S^4/L^4)\}$
Three-point star (L = length of one arm)	$R_g = (\varrho/6\pi L)\{\ln(2L/\alpha) + \ln(2L/S) - 1.071 - 0.209(S/L) + 0.238(S^2/L^2) - 0.054(S^4/L^4)\}$
Four-point star	$R_g = (\varrho/8\pi L)\{\ln(2L/\alpha) + \ln(2L/S) + 2.912 - 1.071(S/L) + 0.645(S^2/L^2) - 0.145(S^4/L^4)\}$
Six-point star	$R_g = (\varrho/12\pi L)\{\ln(2L/\alpha) + \ln(2L/S) + 6.8512 - 3.128(S/L) + 1.758(S^2/L^2) - 0.490(S^4/L^4)\}$
Eight-point star	$R_g = (\varrho/16\pi L)\{\ln(2L/\alpha) + \ln(2L/S) + 10.98 - 5.51(S/L) + 3.26(S^2/L^2) - 1.17(S^4/L^4)\}$

Table 2. Performance of various electrode configurations in 10,000 Ω-cm homogeneous earth. These values were calculated using the equations in this digest.

Electrode configuration	R_g (Ω)
Horizontal wire, 1.3 cm in diameter, 4 m long, buried 2 m deep.	17
Driven rod, 1.6 cm in diameter, driven to 3.5-m depth.	29
Two driven rods, 1.6 cm in diameter, connected in parallel, 2 m apart, driven to 2-m depth.	28

For a given length, a straight wire will have the lowest resistance. Resistance also decreases as the number of arms in a radial array increases, as shown in Figure 10.

In some regions of seasonal frost and permafrost, the procedures for installing grounding rods have been experimentally modified to reduce the resistance to ground. In experiments described by Delaney et al. (1982) and Sellmann et al. (1984), vertical holes with diameters larger than grounding rods were

Conductive backfills

10. Resistance vs number of arms in a radial-array horizontal electrode. A one-arm array has a length of 2L.
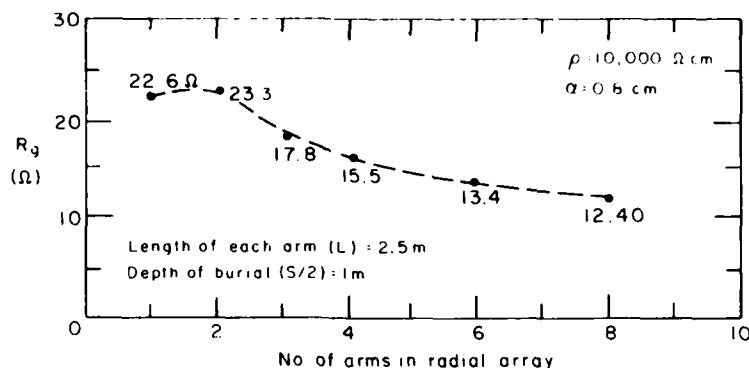
excavated in permafrost either by shaped charges or by drilling. Grounding rods were then emplaced and the holes backfilled with a mixture of either soil, salt and water or just soil and water. Reference electrodes were driven into the ground for comparison purposes.

The use of salt in the backfill material reduced R_g compared to the other backfill by amounts ranging from slight to nearly an order of magnitude. In marginally frozen silt (0° to -2°C), R_g decreased from about 1200 Ω for a driven rod to 145 Ω for a vertical rod emplaced in an excavated hole and backfilled (Sellmann et al. 1984). In very cold silt (-7° to -10°C), R_g decreased from 6700 Ω to only 4500 Ω. Backfilling with a mixture of soil and water without salt improved R_g only during the thaw season. Since these experiments began several years ago, the values of R_g at some of the test sites have continued to lower. Salt may be migrating away from the electrodes due to diffusion or infiltration or both and may be causing some thaw, thus increasing the "effective diameter" of the electrode (Sellmann et al. 1984).

The reduction in resistance by using this method probably depends primarily on the permeability and the unfrozen water content of the soil. If this is true, the technique is likely to be most useful in permafrost regions where fine-grained soil is no more than a few degrees below freezing and where coarser-grained material has a low ice content and retains some permeability when frozen. It should be especially useful in regions where a significant seasonal thaw layer develops, creating favorable conditions for the migration of the salt (unless the material is very coarse and salts leach away). In seasonal frost areas, the salts would be likely to leach away rapidly in the summer. This technique may also improve a ground by reducing the contact resistance between the elec-
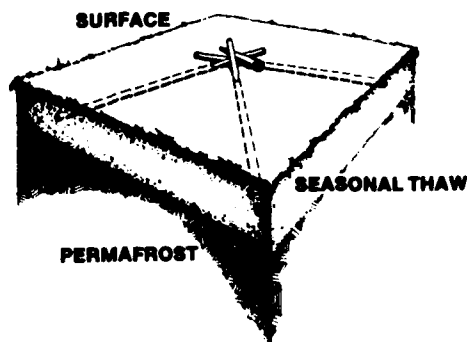
11. Configuration of nearly horizontal electrodes placed in the thawed active layer. (From Sellmann et al. 1984.)

trode and the surrounding soil because the salt prevents an ice layer from forming around the electrode.

One grounding option for temporary summer operations is to place nearly horizontal electrodes in the seasonally thawed layer and pour salt solution onto the surface along each rod (Fig. 11). Sellmann et al. (1984) tested this method and concluded that it "may be applicable to winter installations if a large quantity of salty water is used and a permeable organic surface mat exists."

The common practice of pouring water (without salt) around an electrode once it is driven into the ground will have a variable effect on R_g. In regions of intense cold, it is likely that the water will rapidly freeze around the electrode and cause high contact resistance. In regions of seasonal frost, this practice may lower R_g by washing fine soil particles, with unfrozen water on the surfaces, into contact with the electrode.

Alternatives to grounding

When expedient grounding is necessary and it is impossible to install an electrode, the U.S. Army Corps of Engineers (1973) recommends that surface contact with the earth should be made. This method is not likely to produce specified resistance-to-ground values, but it may be the best option under the circumstances. If earth contact is impossible because of ice or snow cover, equipment should be bonded to reduce the risk that different electrical potentials will develop on each piece of equipment. The potential developed on the bonded system will be different from that of the earth, so an electrical hazard remains. With either surface contact or bonding, extra precautions should include isolating the equipment and using better electrical insulation.

Determining electrode resistance

Calculations of R_g for regions of seasonal frost and permafrost should use a resistively layered earth model. Tagg (1964) theoretically considered the effect of the depth of grounding electrodes in different thicknesses of horizontally layered earth. He presented a method for calculating the resistance of a vertical electrode in layered earth. Arcone (1977) calculated resistances in one- and two-layered earth for vertical rods or horizontal wires and compared the results to the theoretical results of Sunde (1949). Arcone showed that a horizontal wire is preferable to a vertical electrode for achieving the desired R_g for ground conditions similar to those expected in a permafrost setting. For example, if the earth is frozen below 1 m, the resistivity of the unfrozen layer is 10,000 Ω-cm, and the resistivity of the permafrost is 1,000,000 Ω-cm, then a 12-m-long, 5-cm-radius vertical grounding rod will have an R_g of 900 Ω. By comparison, a 0.125-cm-diameter horizontal wire that is 100 m long will have an R_g of about 100 Ω. A 100-m-long electrode may seem impractical, but it is likely to be more effective and easier to install than a long rod driven into permafrost.

The resistance to ground should be measured to ensure adequate performance. A standard procedure for measuring R_g is the fall-of-potential method described by Tagg (1964).

Conclusions

- The chance of finding and developing a low-resistance grounding site decreases greatly when moving towards polar regions from the zone of seasonal frost to the discontinuous and continuous permafrost zones.

- Large seasonal variations in the resistance to ground can be expected in areas of frozen ground. Grounding may not be difficult during the summer but will likely become a problem when the surface layer freezes.

- The search for suitable grounding sites can be aided by geophysical methods that locate low-resistivity (usually unfrozen) earth. A knowledge of an area's topography, vegetation, and surface and groundwater sources can provide good information for locating thawed zones and conductive soils for a grounding site.

- Multiple-rod grounding arrays or horizontal grounding configurations can be used to achieve a lower R_g than with a single grounding rod.

- Excavating a large-diameter hole, inserting a grounding rod and backfilling with a conductive backfill can decrease the resistance of a single driven rod.
- Inserting nearly horizontal grounding rods into an unfrozen surface layer and pouring salt water along the surface may produce an acceptable temporary ground.
- The ocean, steel reinforcing bars, metal well casings and natural thaw zones beneath lakes and streams can provide good grounding alternatives.
- It may be impossible to achieve an adequate ground due to frozen earth or ice and snow cover. In this case, electrical hazards can be minimized by establishing surface contact with the earth or bonding all electrical equipment. In either case extra safety precautions should be taken.
- More research is required to determine the actual effect of unfrozen water content and temperatures on resistance-to-ground values and recommended grounding procedures in areas of seasonally frozen ground and permafrost.

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